Power Systems of the Future

Five possible pathways to the power system of the future take advantage of powerful external forces and can be shaped by the actions of policymakers and regulators.

Owen Zinaman, Mackay Miller, Ali Adil, Douglas Arent, Jaquelin Cochran, Ravi Vora, Sonia Aggarwal, Minnesh Bipath, Carl Linvill, Ari David, Matt Futch, Richard Kaufman, Efrain Villanueva Arcos, Jose Maria Valenzuela, Eric Martinot, Daniel Noll, Morgan Bazilian and Reji Kumar Pillai

Owen Zinaman, Mackay Miller, Ali Adil, Douglas Arent, Jaquelin Cochran and Ravi Vora are with the National Renewable Energy Laboratory. Sonia Aggarwal is with Energy Innovation, Policy, and Technology, LLC. Minnesh Bipath is with the South Africa National Energy Development Institute. Carl Linvill is with the Regulatory Assistance Project. Ari David is with the Columbia University Business School. Matt Futch is with National Grid. Richard Kaufman is with the Office of the Governor of New York State. Efrain Villanueva Arcos and Jose Maria Valenzuela are with SENER of Mexico. Eric Martinot is with the Beijing Institute of Technology. Daniel Noll is with the U.S. Department of Energy. Morgan Bazilian is with Columbia University's Sustainable Engineering Lab. Reji Kumar Pillai is with the India Smart Grid Forum.

This article draws upon work performed in assembling the report 2015 from the National Renewable Energy Laboratory entitled Power Systems of the Future (NREL/TP-6A20-62611). The work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08GO28308 with the NREL. Funding provided by U.S. DOE Office of International Affairs.

The authors thank the Advisory Group for this study, who provided invaluable guidance and comments: Susanne Ackeby, Swedish Transmission Research Institute; Bo Normark, PowerCircle; Ron Binz, Public Policy Consulting; Susan Tierney, Analysis Group; Lawrence Jones, Alstom Grid; Bosco Astarloa and Katherine Avgerinos, World Economic Forum; Kaare Sandholt, China National Renewable Energy Center; and Ken Locklin, Impax Asset Management. Thanks also go to Karin Haas, Lauren Zwicker, and Scott Gossett for their support throughout the process.

I. Introduction

Around the world, forces are combining to reshape power systems at a rate faster than would have been expected 20 years ago. Power systems appear poised for a revolution. Yet the pathway to transformation is highly sensitive to each local situation, and the technical, economic, and political factors at play—whether global or local—warrant careful examination.

Rapid cost reductions—for example, of photovoltaic modules—have changed the economic landscape for what is feasible. Yet established asset bases, and their supporting business models and regulatory frameworks, still retain significant inertia in most power systems. These longstanding financial and institutional “legacy” arrangements promote incremental change, helping to explain, for example, why the International Energy Agency’s World Energy Outlook 2013 [1] estimates the continuation of fossil fuel dominance globally in the power sector through 2035.

Where, on the spectrum of possibility, will power systems of the future land? Custodians of these systems are increasingly charting a course toward reform that achieves lower carbon intensity, cost-effectiveness, accessibility, reliability, resilience, and embedded smart, real-time control and services. However, it is unlikely that the same transformation will occur everywhere, because in each context the power system of the future emerges from the interacting forces of policy, regulation, global market forces, business model innovation, technological innovation, and consumer behavior. In the language of ecology, power systems are complex dynamical systems, and scientific research across multiple domains reinforces that such systems have “critical points” marking a shift to a new regime [2,3].

Are power systems reaching such a threshold? Will they transform incrementally, or will large evolutionary leaps be unleashed? Are there leapfrog opportunities that employ new technologies, policies, and business models? With trillions of dollars invested in physical infrastructure and institutional arrangements, and trillions more needed to achieve energy access and sustainability in the next 50 years [1], the answer is worth exploring.

Here, we suggest five illustrative pathways for power systems of the future, identified by an international team of leaders convened under the 21st Century Power Partnership, an initiative of the Clean Energy Ministerial.¹ This article discusses steps that can be taken to harness the “winds of change” to foster positive transformation.

Many voices have emerged on this issue. This article aims to build upon recent developments and thought leadership on this issue, synthesizing the critical frameworks for decision making on transformation pathways. The goal is to provide a grounded view that can

¹ The Clean Energy Ministerial is a global forum to share best practices and promote policies and programs that encourage and facilitate the transition to a global clean energy economy. Visit www.cleanenergyministerial.org for more information. For more on the 21st Century Power Partnership, visit www.21stcenturypower.org.

enable sound and proactive choices by decision makers. The focus extends from technology to business models to the institutional arrangements that enable orderly investment and reliable system operation while driving transformation that aligns with policy goals. The topics discussed in this article are expanded upon in greater detail in Zinaman et al [4].

II. Ten Trends Driving Power System Evolution

The “*utility of the future*” can largely be described by the dynamic between regulation, technology innovation, and business model evolution. However, the “*power system of the future*” is driven by a more complex set of features. The regulatory/utility dynamic is still a dominant component, but the full complex and dynamic system responds to the following broader set of cross-cutting trends.

Renewable energy cost reductions. Cost reductions in renewable energy (RE) are driving rapid deployment and are encouraging both power system interdependence *and* independence. Bulk power system interdependence and coordination is growing in many jurisdictions. At the same time, the cost of RE is falling for small customers, and the desire for choice and autonomy is growing. The result is two countervailing trends: one toward greater cohesion and one toward greater decentralization. Some [5, 6, 7] have postulated an increasing shift toward “defection” from the traditional utility/customer relationship. Others [8, 9] articulate the critical role of the centralized generation, transmission, and distribution system. Still others [10] articulate an increasing intelligent, heterogenous “system of systems.”

Innovations in data, intelligence, and system optimization. There is an increasing interdependence of information technology and energy technology, with smarter grids opening pathways to greater functionality and active management of more diverse sets of resources providing a range of services that can be monetized in energy markets. Granular data on power system performance and big data analytics can reveal investment needs for grid enhancement and inform the locational value of distributed energy resources, such as distributed generation and storage [11]. The forces of data and intelligence are also sharpening the focus on cyber security, open access to data, and consumer privacy protections.

Energy security, reliability, and resilience goals. In many settings, imports of coal, oil, and natural gas are raising energy security concerns, exacerbating current account balances, and driving increased interest in efficiency and locally developed RE. In other cases, abundant supply and use, particularly of natural gas, offer increased opportunity for low-cost utilization,

addressing some environmental policy goals including local air quality, but have also raised questions regarding longer-term pathways toward lower carbon intensity, price volatility, and geopolitical considerations. The economic potential of RE—and the ability of RE to mitigate energy security concerns—varies widely by country, determined primarily by abundance of resource and distance from load. Grid resilience has increased in importance as extreme weather events occur more frequently. Instead of reinforcing existing systems, which are dominated by a hub-and-spoke structure and use of redundancies to maintain reliability, resilience planning considers mechanisms to increase how flexible the system is, so that critical portions of the system can come back online both quickly and independently in the event of an outage.

Evolving customer engagement. Customer engagement is changing power system dynamics in two ways. First, customer preferences are more directly driving investment trends (e.g., through energy-efficient appliances, distributed generation, electric vehicles, smarter homes). Second, technology innovations are enabling a step change in how customers impact energy supply and demand. Historically, largely inelastic demand led to sharp system peaks, so power system planning, regulation, and market design treated demand as a fixed target, with utilities and grid operators building a dispatchable supply stack to meet it. Direct consumer participation necessitates changes to planning practices and holds the potential to encourage changes to surrounding market designs. At a time when renewable electricity is increasing variability on the supply side, intelligent demand will be an increasingly dispatchable resource [12].

Bifurcated energy demands. With some exceptions, the global energy landscape has bifurcated into areas of rapid growth and areas of flat or decreasing demand. Many emerging economies are exhibiting strong growth, industrialization, and rapid urbanization [13]. With relatively smaller asset bases, these settings provide interesting opportunities for innovation and technology leap-frogging. Meanwhile, the U.S., EU, and Japan, among others, are marked by slow demand growth [14, 15, 16]. These power systems are increasingly marked by growing energy efficiency programs, and could also see decreases in peak demand due to the rise in distributed generation and demand response. These unique trajectories will strongly shape planning strategies and opportunities for power system transformation.

Increased interactions with other sectors. Globally, power systems increasingly compete for scarce water and land resources, sharpening debates about the sector's evolution; but they also encourage improved accounting approaches. Parallel evolutionary processes taking place in the

built environment also need to be accounted for in power system planning. Electrification of transport, although still at relatively low levels, has the potential to significantly impact power system needs and opportunities [17], [18]. If production of shale gas increases globally, gas generators may compete with other critical sectors for these domestic resources, leaving policymakers to contemplate interventions which distribute resources in alignment with national objectives. And industrial consumers, already facing competitive pressure in the global economy to cut costs, are increasingly turning to RE to reduce net energy costs.

Local and global environmental concerns over air emissions. Poor air quality stemming from fossil fuel emissions contributes to acute public health problems at the local level [19], [20]. At a global level, fossil fuel use contributes significantly to climate change [21]. The local and global costs of fossil fuel pollution occur largely outside the power sector, are more difficult to account for, and thus, historically have not been explicitly included in planning processes. But in the 21st century, both concerns—air quality and climate change—are contributing to changes in power system policy and planning.

Energy access imperatives. As part of global agreements to speed economic development and opportunity, there is growing momentum and political will to accelerate energy access to all people. Expanding finance and technology options are providing tailwinds for these energy access goals, but significant investment challenges remain the norm.

Increasingly diverse participation in power markets. Participation in power market ecosystems is diversifying around the world. In emerging economies, where many power sectors have been state-owned, there is a push to boost investment by opening the sector to more independent power producers. In more mature power sectors, this trend is taking the shape of greater direct consumer power market participation, from generation to demand response. These diversification trends, driven by a need to respond to legacy challenges, will add a layer of complexity to power systems of the future.

Revenue and investment challenges. At high RE penetration, supply-related revenue challenges can emerge—at the bulk-power/wholesale level—as abundant wind and solar energy enters the market at essentially zero marginal cost, and reduces use of existing conventional thermal generators. At the customer retail level, distributed photovoltaic and energy efficiency both reduce retail electricity consumption, raising revenue concerns for some electric utilities and

impacting perceptions of investment risk and creditworthiness. Network expansion is facing similar pressure; as falling revenues squeeze typical investors, the need for additional network investment at both the distribution and transmission levels is rising [22].

III. In Focus: Power Sector Finance

The trends discussed in Section II are pushing power systems out of the status quo. But these trends alone do not give a coherent picture of power systems of the future. Power sector finance will influence real options and shape trajectories. An estimated \$19.3 trillion of investments in electricity supply infrastructure are needed over the next 20 years to meet projected demand and stated environmental objectives [23]. Investment trends will evolve differently across local and regional contexts, but there are common factors that underpin the power sector value proposition. Nine key variables (discussed in detail in [4]) will influence investment trends in the power sector.

Regulations on commercial banking risk. Commercial and wholesale banks, through syndicated loans, have contributed 71-77 percent of infrastructure project finance globally over the past five years [24]. If increasingly stringent capital requirements come into effect, then the appetite of banks for providing capital for long-term illiquid infrastructure projects may continue to decline. This might result in a gap in power sector financing, though this gap could potentially be met by investors such as international banks, or insurance companies and pension funds.

Risk-premium environment for investments. Investors provide capital at a cost that reflects the perceived risk and expected return relative to available “risk-free” investments. As the financial and investment community’s perception of risk fluctuates, investors demand different return profiles to compensate them for these risks. This behavior alters the demand for different investment vehicles and leads to changes in the mix of investors for new power sector infrastructure.

Interest rates on government bonds. In today’s historically low-yield environment, investors may look toward “spread assets,” such as infrastructure debt and project finance, and to new structures to maximize the income potential of their portfolios. Thus, structures dedicated to providing investors with long, steady streams of income (e.g., yield companies) have become attractive in the U.S. market. Conversely, if interest rates were to increase, government bonds might offer a more attractive balance of risk and return.

Capital availability from development authorities. The availability of government-supported financing may be a key variable in many regions, particularly those without established capital markets. This might occur via direct low-interest financing or loan guarantees from domestic or regional development banks. Alternatively, international development agencies may also provide financing. The availability and terms of such funds will drive how quickly these markets are able to develop power sector infrastructure.

Tax structures. The evolving types of tax structures available in various jurisdictions for power sector infrastructure investments could be a key variable influencing investment trends. Using the U.S. as an illustrative example, master limited partnerships (MLPs) and real estate investment trusts currently enjoy tax benefits not afforded to RE generation and other power sector assets. Modifying the tax code to allow RE generation assets to qualify for the same treatment as oil and natural gas production within the MLP structure may result in attracting more retail and institutional investors to the power sector.

Credit rating of electric utilities. Utilities have historically enjoyed relatively high credit ratings and thus access to inexpensive capital, because revenues were seen as stable. Future revenue streams are contingent on regulatory structures and other variables and will determine whether this access to inexpensive capital will persist. The cost of capital for utilities seems set to face consistent upward pressure, as new entrants will likely target high-income customers. If creditworthiness deteriorates, investors will demand higher risk premiums, leading to changes in investor types and the potential for different investment vehicles to feature more prominently.

Price and availability of inputs. The evolution of both price and availability of fossil fuels will continue to impact investment in the generation sector. The global dissemination of shale gas recovery equipment and associated technology innovation, combined with jurisdiction-specific environmental regulations, will be key variables influencing the extent of investments in natural gas generation. The price and availability of various renewable technologies depend on local and global supply chains, and will also be a key variable.

Market structure and valuation constructs. Revenue sufficiency in the power sector is a function of how the market values various products, such as energy, capacity, and ancillary services. Thus, investment trends are impacted by how the electric sector is organized—vertically integrated versus restructured settings—which has implications for cost recovery, investment risk profile, and investment opportunities. They are also impacted by what product

attributes are valued by the market. Such attributes might include flexibility, availability during contingency events, environmental externalities, fuel price hedging, or portfolio risk impacts. As power sectors reorganize or make shifts in their valuation constructs, investment trends will likely shift, as well.

Policy and regulation are levers that influence the previously mentioned variables, and therefore, the power sector investment climate, in general. For example, local content requirements may impact generation and supply chain investments. Regulatory approaches to DERs will impact utility creditworthiness and the health of installer and/or third-party leasing markets. Tax structures will influence the structure of appropriate investment vehicles.

IV. Understanding Different Types of Power System Transformation

The trends outlined in Sections II and III provide a sense of the forces impacting the power sector, but changes to the power system are path-dependent, so the fuller picture only emerges by examining how power system legacies (technological, financial, and institutional) shape the landscape of options. Heavier legacies generally promote cautious gradualism, whereas lighter legacies enable more rapid change. In this context, power system transformation can be measured by both the extent and speed of change. **Figure 1** illustrates this framework for transformation, the resulting four quadrants are described in more detail below, and select literature is located within this landscape.

Figure 1: Types of Strategic Change

Adaptation. The Adaptation quadrant of power system evolution represents a continuation of slight, incremental change, in which neither the organization of the power system or the rate of change are significantly altered. Examples are the “Fight” and “Flight” models described by

Bloomberg New Energy Finance [25] and the Top-Down Grid Expansion pathway discussed by various observers (e.g., [26]).

Reconstruction. The Reconstruction quadrant represents a relatively short period of change (three to five years) that reorganizes the major functions and roles of power system players. Reconstructive change is not fundamental—meaning that whereas roles change significantly, the conventional categories of generation, transmission, and distribution still apply. Thus, the fundamental structure of the power sector does not change deeply. Reconstruction in the 21st century tends to include a greater emphasis on clean energy, smarter grids, and energy efficiency, as provided through a mix of administrative and competitive processes. An example is the Mexico Energy Reform [27].

Evolution. The Evolutionary quadrant represents a more dramatic power system change, carried out over a relatively longer period of time (10 to 20 years). Compared to the Reconstruction quadrant, the literature and examples emerging in this quadrant imply more fundamental changes to supply, delivery, and demand. Demand-side participation from all consumer classes is anticipated to grow dramatically, implying crucial roles for coordination of distributed generation, various types of energy storage, electric vehicle charging, and demand response. With regard to energy delivery, the Evolutionary pathway implies a greater degree of coordination at the distribution network level, as well as new types of interaction between distribution and transmission networks. With regard to energy supply, the flow of investment is likely to change significantly from centralized generation sources to a more balanced mix of centralized and distributed generation. Some important roles will remain for monopoly utilities, to the extent that these incumbents can bring to market enough innovation to satisfy demand, or present the lowest-risk pathway forward. In many cases, the “evolution” pathway is a move toward more comprehensive power system optimization, leveraging the suite of new technologies that have become available in the 21st century. Key literature and real-world examples of this evolutionary path are RIIIO [28], EPRI: The Integrated Grid [8], Reforming the Energy Vision (REV) [29], CSIRO: Rise of the Prosumer [30], and IFC (Fragmented Services) [26].

Revolution. The Revolutionary quadrant represents power system transformation that is both fundamental and sudden. Drivers of such a change could be, for example, the sudden onset of large-scale grid-defection, with dramatic cost improvements in distributed generation and storage

rapidly eroding the cost advantage of centralized grids. Some reports attempt to evaluate the economics of this possibility—for example, in mature markets, “The Economics of Grid Defection” [6], and in markets with limited energy access, “Community Energy” as articulated in “From Gap to Opportunity” [26].

Figure 2 illustrates how some of the possible future scenarios for power transformation map into this landscape. Representative examples highlight that many transitional pathways are either in process or have been explored, and one might anticipate that the landscape will become increasingly heterogeneous.

Figure 2: Illustrative Landscape of Reports on Emerging Power System Models

V. Pathways to Power Systems of the Future

Here, we suggest five illustrative pathways for power systems of the future, identified by an international team of leaders convened under the 21st Century Power Partnership, an initiative of the Clean Energy Ministerial. These pathways have already begun to emerge, and we will discuss steps that can be taken to harness the “winds of change” to foster positive transformation.

Figure 3(a) indicates the five pathways and places them in the framework of the extent and speed of change. The pathways are the (1) adaptive “Next-Generation Performance-Based Regulation” pathway, (2) reconstructive “Clean Restructuring” pathway, 3) evolutionary “Unleashing the DSO” pathway, and the “Bottom-of-the-Pyramid (BOP)” coordination pathways, which include the (4) adaptive “Bottom-Up Coordinated Grid Expansion” strategy and 5) evolutionary “Bundled Community Energy Planning” strategy. **Figure 3(b)** positions these pathways next to their “adjacent” starting points, to illustrate potential trajectories for power

system transformation. This is not to suggest however that the adjacent pathways are the only options, or that they are mutually exclusive. Combinations of different pathways will likely arise.

Figure 3(a): Illustrative Pathways of Power Systems of the Future

Figure 3(b): Illustrative Pathways Linked to ‘Adjacent’ Present Power System Status

A. Next-generation performance-based regulation pathway

In this pathway, vertically integrated utilities retain their principal role in the power system, but the regulatory framework that governs them shifts toward rewarding revenue based on *performance*, rather than compensating utilities for incurred costs. In doing so, the monopoly of the electric utility and its associated structures are not only preserved, but expanded. The postulated utility death spiral is mitigated by incremental regulatory adaptations toward output-based incentives and ratemaking practices; as a result, the vertically integrated utility is

increasingly motivated to incorporate the very technologies that once threatened its existence. However, the utility is more actively competing with customer grid defection—a future that is increasingly feasible as technology continues to evolve. In response to this threat, the utility strives to offer a suite of transactive energy management services, as well as cost-competitive tariffs and high levels of customer service.

Despite preserving the system’s institutional structure, technology companies—particularly those in active grid management or data analytics—must inevitably be cleared by the utility; this may serve as a barrier to market entry. As a result, the utility in this pathway may slow the pace of innovations, or may be more likely to expose ratepayers to its missteps as it attempts to keep up with innovation. However, for many jurisdictions, this incremental transformation may appear to be the lowest-risk opportunity for harnessing the potential of power sector technology innovations.

This pathway represents an *adaptive* shift, rooted in cautious incrementalism—a controlled progression toward power sector modernization in a vertically integrated utility paradigm.

B. Clean restructuring pathway

Twenty years of global experience with wholesale power market restructuring has generated a wealth of lessons learned. Namely, regulators have adapted approaches and market designs to better incentivize and integrate clean energy investments. The “Clean Restructuring” pathway represents an update to previous power system restructuring, improving longstanding objectives such as reduced electric rates and a diverse generation portfolio, but also including novel elements designed to incorporate clean energy technologies and reduce environmental impact. Clean Restructuring also presents an opportunity to create forward-looking wholesale market frameworks that might eventually incorporate dynamic and participatory distribution systems.

This pathway is “big bang” in that it relatively quickly reshuffles roles, responsibilities, and investment flows. But it is also more of a realignment than a transformation in that it leaves in place the well-known actors such as independent system operators, independent power producers (IPPs), and distribution utilities. Thus, this pathway represents a *reconstructive* shift from the regulated vertically integrated utility paradigm. The Mexico Energy Reform is one incarnation of the Clean Restructuring pathway. Recent energy market reforms proposed in

South Africa [31] and pilot projects in China [32] are also variations on this pathway, as are nascent moves toward an “energy imbalance market” in the western United States [33].

C. Unleashing the DSO pathway

There is significant latent potential for distribution system operators (DSOs) to contribute to the safe and efficient management of the power grid via increased coordination with transmission market operators (TMOs). With clear regulation and policies in place that establish roles, responsibilities, technical standards, and market frameworks, the DSO and its growing portfolio of distributed energy and flexibility resources might be unleashed for the benefit of all.

In this pathway, DSOs are transformed into distribution-level retail market operators who use dynamic price signals to invite consumers, marketers, and other service providers to participate. These low-voltage markets coordinate with bulk power markets on both a technical and financial basis, with coordination hinging on clearly delineated roles and responsibilities, on information and communication technologies that use open-access data architecture, as well as a regulatory framework that encourages the incorporation of technological innovations. Consumer data, and access to it, will likely play a significant role in the success of the model. Regulators and policymakers must balance consumer privacy concerns with the need to allow commercial entities to make effective use of energy data. Low-voltage markets, fundamentally oriented toward encouraging innovation, encourage private investment across various investor classes. Consumers can invest private capital in distributed energy resources (DERs) and energy management hardware. Also, with appropriate regulatory support, investments in bulk power generation, transmission, and distribution infrastructure can remain relatively low-risk, despite the large-scale shift in the underlying regulatory framework.

This pathway represents an *evolutionary* shift—a gradual yet fundamental change—from a narrow set of utilities, system operators, and IPPs to a thriving ecosystem of diverse market actors. Such changes could be triggered by policy directive or decreasing electric utility credit ratings. A jurisdiction’s transition might begin with piecemeal regulatory actions (e.g., revenue decoupling, performance-based rate incentives, time-of-use rates, distributed generation standby rate formulation, low-voltage demand response programs), similar to those adopted in the Next-Generation Performance-Based Regulation pathway, progressing to a more unified, deliberate vision of power sector transformation with a larger emphasis on facilitation of liberalized retail power markets. This pathway, from a technical and regulatory standpoint, is significantly more

complex than historic transitions; however, there can be many tangible, broad-based benefits to consumers and society as a whole—namely, systems costs, resiliency, and reliability. Consumer participation is critical for a successful ecosystem, and that participation hinges on demonstrating the value of participation to the customer, as well as on opening up access to data.

D. The bottom-of-the-pyramid coordination pathways

Accelerating energy access has been a chronic challenge for decades. With technology costs declining, novel approaches to energy access are emerging, ranging from super-efficient solar home systems to community microgrids. Citizens with low energy access represent a heterogeneous yet growing market segment in many developing countries. Energy-poor communities have unique starting points with respect to market sophistication and development. As a result, effective energy-access solutions require significant customization, making it difficult to scale up solutions on a global basis.

Nonetheless, a coherent solution-set can be envisioned through the lens of recent technical and business model innovations. We identify two related, but distinct, pathways emerging for expanding energy access: *bottom-up coordinated grid expansion* and *bundled community energy planning*, which both take advantage of synergies arising in existing solutions.

Customers in the expansive Bottom-of-the-Pyramid market face energy shortages due to unreliable supply or lack of grid connectivity. Energy poverty is often tackled through three approaches: fragmented energy services, community-scale energy services, and expansion of traditional grids. Each approach entails differences in terms of sophistication, cultural attributes of target customer groups, and the scale of required investments.

Bottom-up coordinated grid expansion. This pathway bridges two existing energy service paradigms: community-scale energy services and top-down grid expansion. Currently, these paradigms can occasionally be in competition. The new pathway identifies steps that enable coordinated planning and operation across these paradigms to accelerate energy access.

In most countries, comprehensive grid coverage is ultimately being desired and linked to national social and economic development. The design of this pathway couples the incremental pace of central grid expansion with comparatively fast, affordable, and innovative expansion of community-scale mini-grid systems. The key design innovation in this pathway is technical and regulatory backwards-compatibility of mini-grids to the central grid.

Bundled community energy planning. This pathway also entails a convergence of two existing paradigms: community-scale energy services and fragmented energy services. A market-oriented integration of these independent business models exposes latent complementarities. Due to strong context-specific underpinnings in both these solutions, this pathway focuses on realizing beneficial commercial models that integrate both approaches. The key design feature of this path is an integrated business plan that hinges on clear regulatory and policy signals to define market needs, clarify value propositions and unlock gaps in financing.

VI. Design, Policy and Regulation, and Finance

Three key levers are available to decision-makers to support the emergence of desired outcomes: design, policy and regulation, and finance.

Design. The underlying technologies and system designs of power systems are central to power system transformation. At the same time, these characteristics are also path-dependent on legacy institutions and policy goals; for example, the extent of existing power market liberalization is a key variable. Institutional fluency with managing DERs is another. Future pathways are guided by a desire to reap the potential benefits of technological advancements, and the extent of a particular jurisdiction’s ability to do so. The resulting mix and distribution of benefits realized will be highly context-specific. Spanning most pathways is the potential for a sizable influx of market and consumer data. The extent to which those data are available to and used by various market players will heavily influence outcomes, particularly with respect to expanding consumer participation, sector investability, and efficient system operation.

Policy and regulation. Policy provides support for public/private partnership research, funding for demonstration projects, and deployment incentives that collectively can give investors clear signals about the current and future direction of the market. Policy also provides guidance—and where necessary, authorization—for the regulatory frameworks that govern these pathways. For the first time in history, technological innovation is making it possible to realize cost-effective, reliable, *and* clean power systems. Seeking to realize this future, regulation can seek to incorporate technological innovation, as well as competition to promote such innovation. The extent to which regulation is structured to decrease barriers to market entry—or avoids the selection of “winning” technologies and products—is a key variable influencing outcomes. Policies will likely also provide guidance on what levels of vertical market power are acceptable

throughout various stages of transformation, and inform the regulator on the balancing act of privacy concerns versus open access to data.

Finance. The investability of the power sector, as well as the health and composition of participating investor classes, will influence the rate and extent of power system transformation. Investability hinges on policy, regulatory, and political stability, on the financial health of natural monopolies in the sector, and on robust capital markets. The profile of participating investor classes is influenced by many variables (see Section III).

VII. Conclusion

Power systems of the future are emerging now. Whether in countries with mature power systems, emerging economies, or the least-developed countries, technology innovation has opened up important new avenues for power system transformation. Each pathway articulated in this article takes advantage of external forces, identifying levers that policymakers and regulators can use to shape the power system.

Whether the trends outlined in Section II are “headwinds” or “tailwinds” will depend on the orientation set by decision-makers for their power systems. Policymakers and regulators can choose to let these external forces determine how power systems unfold, or they can promote policies and build regulatory and finance frameworks that drive the transformation toward a desired vision. As a final organizing principle, early and frequent stakeholder engagement will encourage the emergence of modern power systems that accommodate a broad set of interests and best serve citizens and energy customers.

With these principles in mind, decision-makers in the power sector will be better positioned to proactively guide a transition to 21st century power systems. Organizing the policy and regulatory landscape to harness today’s trends will speed the arrival of accessible, reliable, and low-carbon energy futures. As the old saying goes, “When you can’t change the direction of the wind—adjust your sails.”

References

- [1] International Energy Agency (IEA), World Energy Outlook. IEA, Paris, France, 2013.
<http://www.worldenergyoutlook.org/publications/weo-2013/>
- [2] R.M. May, S.A. Levin, G. Sugihara, Ecology for bankers, *Nature* 451 (2008) 893–895.
- [3] M. Scheffer, et al., Early warnings of critical transitions, *Nature* 461 (2009) 53–59. DOI:
<http://dx.doi.org/10.1038/nature08227>
- [4] O. Zinaman, et al., Power Systems of the Future, NREL/TP-6A20-62611, National Renewable Energy Laboratory, Golden, CO, 2015.
- [5] Barclays, The Solar Vortex: Credit Implications of Electric Grid Defection. Barclays Credit Research, 2014.
- [6] Rocky Mountain Institute (RMI), The Economics of Grid Defection, RMI, Boulder, CO, 2014. http://www.rmi.org/electricity_grid_defection
- [7] UBS, Q-Series® on Global Utilities, Autos & Chemicals: Will solar, batteries and electric cars re-shape the electricity system? UBS, Zurich, Switzerland, 2014.
<http://knowledge.neri.org.nz/assets/uploads/files/270ac-d1V0tO4LmKMZuB3.pdf>
- [8] Electric Power Research Institute (EPRI), The Integrated Grid: Realizing the Full Value of Central and Distributed Energy Resources, EPRI, Palo Alto, CA, 2014.

- [9] P. Kind, Disruptive Challenges: Financial Implications and Strategic Responses to a Changing Retail Electric Business. Prepared for Edison Electric Institute. Washington, D.C., 2013. Accessed Sept. 2014.
<http://www.eei.org/ourissues/finance/documents/disruptivechallenges.pdf>
- [10] M.F. Ruth, B. Kroposki, Energy systems integration: An evolving energy paradigm, *The Electricity Journal* 27(6) (2014) 36–47. DOI: <http://dx.doi.org/10.1016/j.tej.2014.06.001>
- [11] P. Denholm, R. Margolis, B. Palmintier, C. Barrows, E. Ibanez, L. Bird, J. Zuboy, [Methods for Analyzing the Benefits and Costs of Distributed Photovoltaic Generation to the U.S. Electric Utility System](#). 86 pp.; NREL Report No. TP-6A20-62447, 2014.
- [12] IEA Renewable Energy Technology Deployment (IEA-RETD), Residential Prosumers – Drivers and Policy Options (RE-Prosumers). Sept. 2014 (Revised version of June 2014). IEA, Paris, France, 2014. http://iea-retd.org/wp-content/uploads/2014/09/RE-PROSUMERS_IEA-RETD_2014.pdf
- [13] World Bank, Global Economic Prospects: Shifting priorities, building for the future. World Bank Group Flagship Report. Washington, DC, 2014. DOI: <http://dx.doi.org/10.1596/978-1-4648-0387-1>
- [14] U.S. Energy Information Administration (EIA), U.S. Electricity Sales Have Decreased in Four of the Past Five Years, *Today in Energy*, 2013.
<http://www.eia.gov/todayinenergy/detail.cfm?id=14291>
- [15] Eurostat, Consumption of Energy, European Commission, Brussels, Belgium, 2014.
http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Consumption_of_energy
- [16] Statistics Japan, Chapter 10 Energy and Water: Electricity. Tokyo, 2014.
<http://www.stat.go.jp/english/data/nenkan/1431-10e.htm>
- [17] R. Green II, L. Wang, M. Alam, The impact of plug-in hybrid electric vehicles on distribution networks: A review and outlook, *Renewable and Sustainable Energy Reviews* 15(1) (2011) 544–553. DOI: <http://dx.doi.org/10.1016/j.rser.2010.08.015>
- [18] F. Mwasilu, J. Justo, E. Kim, T. Do, J. Jung, Electric vehicles and smart grid interaction: A review on vehicle to grid and renewable energy sources integration, *Renewable and Sustainable Energy Reviews* 34 (2014) 501–516. DOI: <http://dx.doi.org/10.1016/j.rser.2014.03.031>
- [19] Y. Chen, A. Ebenstein, M. Greenstone, H. Li, Evidence on the impact of sustained exposure to air pollution on life expectancy from China’s Huai River policy, *Proceedings of the National Academy of Sciences* 110 (2013) 12936–12941.
- [20] Environmental Protection Agency (EPA), *The Benefits and Costs of the Clean Air Act from 1990 to 2020*, EPA, Office of Air and Radiation, Washington, DC, 2011.
- [21] Intergovernmental Panel on Climate Change (IPCC), *Fifth Assessment Report*, IPCC, Geneva, Switzerland, 2014.
- [22] M. Hogan, *Power Markets: Aligning Power Markets to Deliver Value*, America’s Power Plan, 2013.
- [23] International Energy Agency, *World Energy Investment Outlook*, IEA, Paris, 2014.
<http://www.iea.org/publications/freepublications/publication/weio2014.pdf>
- [24] T. Ehlers, F. Packer, E. Remolona, *Infrastructure and Corporate Bond Markets in Asia*, Conference Volume of the 2014 RBA Annual Conference on Financial Flows and Infrastructure Financing, 2014.

- [25] Bloomberg New Energy Finance (BNEF), Fight, flight or adapt: How are US utilities coping with distributed PV? BNEF, New York, NY, US Solar Research Note, 2014.
- [26] International Finance Corporation (IFC), From Gap to Opportunities: Business Models for Scaling Up Energy Access. IFC, Washington, DC, 2012.
- [27] Secretaría de Energía (SENER), Energy Reform Key Elements, 2014.
<http://sener.gob.mx/res/prensa/KEY%20ELEMENTS%20OF%20THE%20ENERGY%20REFORM.pdf>
- [28] S. Aggarwal, E. Burgess, Performance-based models to address utility challenges, *The Electricity Journal* 27(6) (2014) 48–60.
- [29] New York Department of Public Service (NY-DPS), Reforming the Energy Vision: NYS Department of Public Service Staff Report and Proposal. Case 14-M-0101, NY-DPS, Albany, NY, 2014.
- [30] P. Graham, T. Brinsmead, S. Dunstall, J. Ward, L. Reedman, T. Elgindy, J. Gilmore, N. Cutler, G. James, A. Rai, J. Hayward, Modelling the Future Grid Forum Scenarios, CSIRO, 2013.
<http://www.greencrossaustralia.org/media/9964676/modelling%20the%20future%20grid%20forum%20scenarios%20pdf.pdf>
- [31] Republic of South Africa Department of Energy (RSA-DOE). Independent System and Market Operator Establishment Bill. Government Gazette 2011;551:34289. Notice 290 of 2011. RSA-DOE, 2011. <http://www.energy.gov.za/files/policies/1-34289%2013-5%20ISMO%20Establishment%20Bill%20for%20Public%20Comments.pdf>
- [32] C. Gao, Y. Li, Evolution of China's power dispatch principle and the new energy saving power dispatch policy, *Energy Policy* 38(11) (2010) 7346–7357.
<http://dx.doi.org/10.1016/j.enpol.2010.08.011>
- [33] Western Interstate Energy Board (WIEB), Energy Imbalance Market Overview, 2013.
<http://www.westgov.org/EIMcr/documents/edt-onepager.pdf>

Additional Reading

International Energy Agency (IEA). The Power of Transformation: Wind, Sun and the Economics of Flexible Power Systems, 2014.
<http://www.iea.org/textbase/npsum/givar2014sum.pdf>

Figure1

Figure2

Figure3a

Figure3b